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COLOR CONTROL IN A MULTICHANNEL SIMULATOR DISPLAY: THE DISPLAY FOR ADVANCED RESEARCH AND TRAINING

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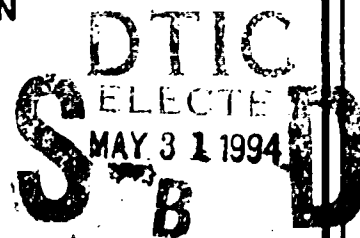
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    This report outlines the principles for color-matching of computer-generated imagery in displays made up of sectors served by several display devices. These principles are discussed with reference to a particular multichannel simulator display for which the display devices are projection cathode ray tubes.

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PREFACE

Three years have passed since the Display for Advanced Research and Training (DART) was moved from its original location into AL/HRA's new building designed to support classified and unclassified aircrew training research. During this period, six DART windows have been continuously operational, and performance of the projection CRTs serving these windows has been tracked through periodic spectroradiometric measurements. Procedures for achieving and maintaining color control in the DART display have been developed and implemented. This report brings together in one place the principles which have guided these procedures and the data which have been collected to document their application.

COLOR CONTROL IN A MULTICHANNEL SIMULATOR DISPLAY: THE DISPLAY FOR ADVANCED RESEARCH AND TRAINING

INTRODUCTION

Improvements in display resolution and field of view can often be obtained by using several display devices, each providing imagery in its sector of the total scene. In some cases, one device projects a high resolution inset while other devices provide the background in lower resolution. In other displays, the contributions of several display devices are juxtaposed to create a composite scene much larger and brighter than any one device alone could produce. Composite displays pose two new problems not encountered with single-device displays: the problem of matching colors across the display sectors (color matching), and the problem of blending display sectors at their adjoining edges (edge blending).

As display technology has advanced toward higher resolution, larger screens, and greater brightness, methods of color specification have been carried along from the earlier stages without reexamination. Database modelers have become sophisticated in cell texturing and photo texturing; display engineers have solved difficult problems of edge blending between adjoining display sectors, and manufacturers have invented many types of projection display devices suitable for large-screen presentations. Yet in the midst of all this technological ingenuity, users of computer-generated imagery (CGI) are still handling color as if all displays were workstation cathode-ray tubes (CRTs). Now that multiple-device displays are the rule rather than the exception, perhaps the color-matching problems of these displays will provide the motivation necessary for a general rethinking and revision of procedures for designing and controlling color in all CGI displays.

This report describes the procedures which have been used in matching the scene colors in a particular six-sector display. The information given will guide people who build or maintain similar displays. By emphasizing the principles which were followed in this case, the report may also encourage CGI users to revise color control procedures for other displays that have different configurations and components.

DESCRIPTION OF THE "DART DOME" DISPLAY
Geometry

The Display for Advanced Research and Training (DART) is a small-scale, dome-type display with imagery partially surrounding an observer seated at the center. Thomas and Reining (1990) have described its design and construction. Geometrically, the DART is a geodesic dome made up of flat, five-sided, rear-projection

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screens. The inset in Figure 1 shows the dimensions of one pentagonal screen.

Twelve such pentagons would make up a complete dodecahedron. The DART has nine pentagonal screens, forming the upper three-quarters of such a dodecahedron; the cockpit occupies the bottom quarter. Figure 1 shows the numbering of these nine screens in relation to screen 1 directly in front of the viewer. The center of each component pentagon is tangent to an imaginary sphere with a radius of about 1 m. When all nine screens are illuminated, the display has a field of view 360 degrees horizontally by about 120 degrees vertically. About 1 cm of the black supporting framework shows at the edges where the screens meet. From the observer's point of view, the display satisfactorily simulates real-world scenery viewed through nine large windows. Thus, the screens are rarely described as "screens"; they are quite naturally referred to as "windows."

Figure 2 shows the position of one projector, the mirror used to fold its light path, and the projection screen. The entire nine-window structure has a diameter of about 7.3 m (24 ft).

Resolution

Barco Data 600 projection CRTs were chosen as the projection devices for the first eight windows. These devices provide a 1,000-line display for each window; addressable pixel size is, therefore, about 5 arc min since some pixels are lost in trimming the display to fit the pentagonal shape. The ninth window is served by a General Electric Talaria light-valve projector.

It should be remembered that "addressable pixel size" merely sets an upper bound on the resolution of a display. Therefore, the resolution of the DART display cannot be better than about 5 arc min. Whether these individually addressable pixels can actually be discriminated by the eye depends on the modulation transfer function (MTF) of the display optics. Kelly (1992) reports MTF measurements made on the DART; his data show that the modulation depth of a line 5 min wide is about 12% for a horizontal line and about 2% for a vertical line. Data on human target detection (Thomas, 1978) indicate that a line 5 min wide can be detected at 4% modulation depth when it is at least 5 min long. Such a line needs to be at least 20 min long to be detected at 2% modulation depth. Under viewing conditions in the DART, therefore, a spot must be larger than 5 min in diameter in order to be detectable by the human eye.

Luminance

With standard unity gain Stewart Lumiglas 130 screens, these projectors provide a maximum white luminance of about 90 cd/m^2 (26
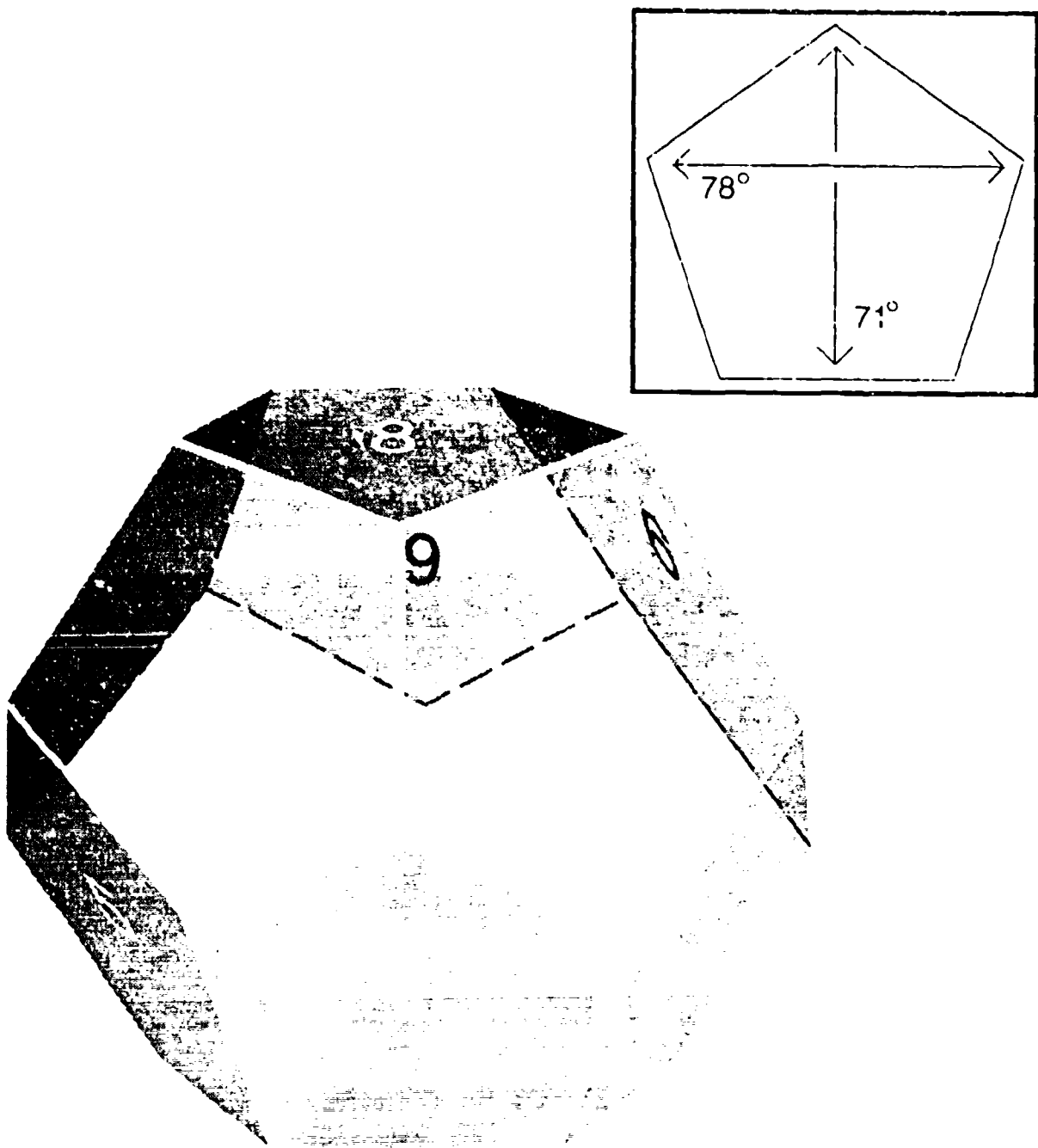
Figure 1
Numbering of DART Pentagonal Screens. Window 1 is directly in front of viewer in cockpit. The viewer's eyes are about 1 m from the center of each screen. Inset shows screen dimensions in degrees of visual angle.

PROJECTOR

LIGHT PATH

MIRROR

OTHER SCREENS

**REFLECTED IMAGE
ON PROJECTION SCREEN**
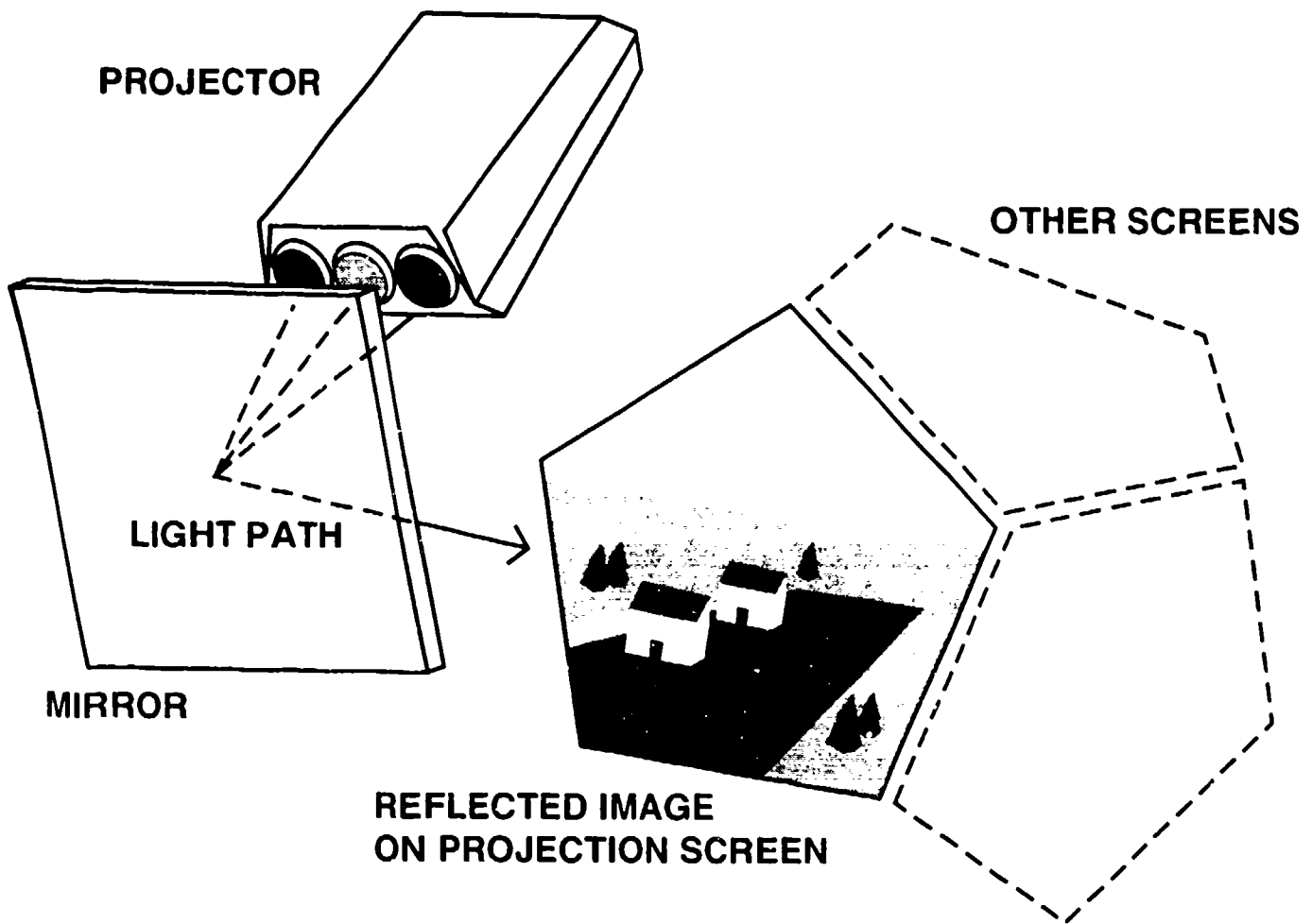
Figure 2
Light Path from One CRT Projector,
Reflected from Mirror to Screen

fL) in a 10% area at the center of the window. This luminance falls off to about 30 cd/m^2 at the edges of the window. Since the average luminance of a typical scene is about 20% of its maximum white, the display is capable of rendering scenes with average luminance about 18-22 cd/m^2.

We have also experimented with placing higher gain screens in some windows. Such screens can increase luminance at the center of the window by as much as a factor of 3. With high-gain screens, edge luminance does not increase; there is, therefore, an overall impression of increased illumination and resolution at the center of the window, while the difference in illumination between center and edges is more noticeable than it is with unity gain screens.

Image Generator Channels

The DART was designed as a low-cost simulator which could be operated with either four or six image-generator (IG) channels. When six channels are available, the simulator may be operated in either of two modes, fixed or head-tracked. In fixed mode, the six channels always serve windows 1-6, providing a horizontal field of view about 110 degrees to the right side and 150 degrees to the left side.

In head-tracked mode, imagery can be supplied to several subsets of the nine windows, depending on head position Window 1 (straight ahead) is never blanked. When the pilot looks upward to his far right, windows 7, 8, and 9 light up while windows 2, 4, and 6 (now behind his head) turn off. When he looks upward to his far left, windows 6, 8, and 9 light up while windows 3, 5, and 7 (behind his head) turn off. A Polhemus magnetic tracker provides information on head position azimuth and elevation. This channel-switching arrangement provides the pilot with the same field of view he would have in a fighter such as the F-15, even though only six IG channels are available.

The next section of this report deals with color matching for windows 1-6, which have been studied over a period of three years. Color matching for windows 7 and 8 will follow the same principles. The additional considerations required to match the light-valve display in window 9 will be discussed in another report on light-valve color matching.

PRINCIPLES OF DEVICE-INDEPENDENT COLOR CONTROL

Digital Color Specification

Color control in digital displays can best be understood by beginning where the technology itself began, namely, with monochrome displays and few "gray" levels. If the pixel in a monochrome display can only be "on" or "off," only 1 bit of information is required to specify its "color." With 2 bits of information available, it is possible to specify four different "gray" or brightness levels; with 3 bits, 8 levels; and with 4 bits, 16 levels.

Different brightness levels are physically produced by varying the voltage at the electron gun which is used to excite the phosphors on the face of the CRT. When there are 4 bits of information controlling the voltage through the digital-to-analogue converters (DACs), the voltage steps are linear with the scale of numbers 0-15. However, the luminance output resulting from these voltage steps is not a linear scale. Luminance varies with voltage in the manner shown in Figure 3. As voltage increases linearly, luminance at first increases slowly, then more and more

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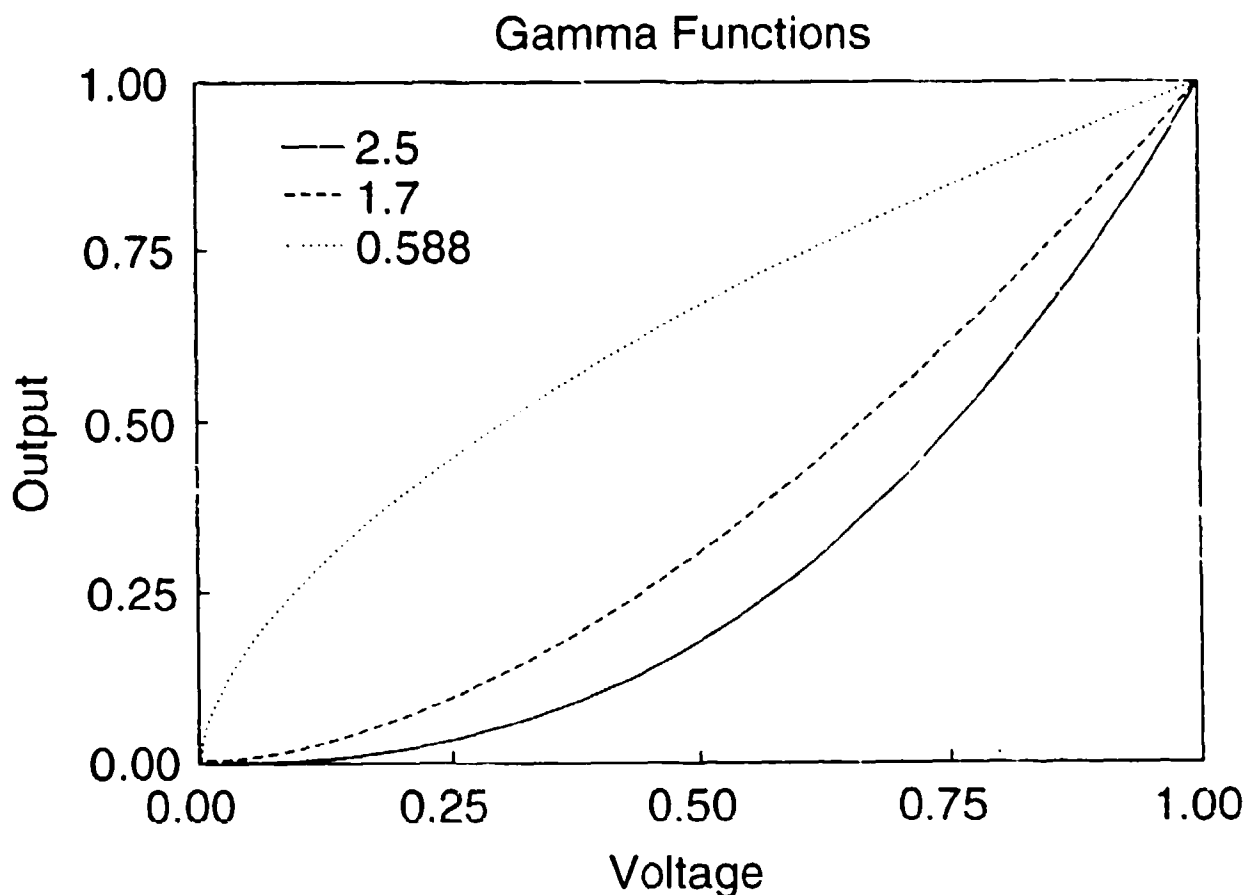
Gamma Functions

Figure 3
Graphs of Gamma Functions. Illustrates possible relations between voltage and luminous output. Gamma values of 1.7 to 2.5 are commonly found in CRTs; a gamma of 0.588 is the inverse of gamma = 1.7.

rapidly. The changes in luminance Y with increasing voltage X can usually be fit fairly well with a power function, $Y = kX^\gamma$, where the value of gamma is greater than 1. Such a function is, therefore, commonly called a "gamma function." It is very important to understand and remember the nature of this gamma function of a CRT display.

Color graphic displays apply the same principles to CRTs in which the single amber or green phosphor is replaced by red, green, and blue phosphors and the single electron gun by three electron guns. The voltage of each of the three guns is controlled in exactly the same manner as in the monochrome case; the number of brightness levels for each of the three colors is determined by the number of bits of information available for use in specifying the

voltage to be applied to its gun. Early color CRTs used only 1 bit per gun: red was either "on" or "off," but the combination of red and green possibilities actually gave four colors: red when red alone was on, green when green alone was on, yellow when both red and green were on, and black when both were off. With the addition of blue, the possibilities were doubled, and the outcomes could include aqua or cyan (when green and blue were on, red off), purple or magenta (when red and blue were on, green off), blue (blue alone on), and white (red, green, and blue all on). These outcomes were possible because the phosphor colors were chosen to take advantage of the trichromatic nature of human vision.[1]

Many color displays still in use can display only 16 colors; this increase from 8 colors was made possible by increasing the information capacity for color specification from 1 bit to 2 bits per color. Meanwhile, monochrome displays had increased in resolution, and most of them came to have 8-bit digital codes for voltage. The resulting 256 levels of luminance thus came to provide a virtually smooth gamma function of voltage. It became very difficult, if not impossible, for the eye to detect the small difference in luminance between successive voltage levels even near the top of the 256-step voltage scale.

The numbers 0-255 thus came to symbolize "how much" light would result when those numbers were converted into voltages by the IG and sent to the projector.[2] When 8-bit color became available, the same numbers came to represent "how much" red, green, or blue would result when the three digital codes (one for R, one for G, one for B) were sent to the three DACs for the three electron guns. It became customary to specify the color for any single pixel or pixel-group as an "RGB code" consisting of three numbers, each in the 0-255 range. Users did not entirely forget that the relation between those numbers and luminance ("how much" red, etc.) is markedly nonlinear, but they did come, through experience, to believe that if the numbers for R, G, and B were all the same number, the result would be "white" if the numbers were high,

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[1]Readers accustomed to the use of pigment colors may find it surprising that the primaries used by CRTs are red, green, and blue rather than red, yellow, and blue. Combining pigment colors results in combining the subtractive properties of pigments; combining phosphors (which emit light) is additive rather than subtractive.

[2]The conversion of the digital (RGB) signal to an analog (voltage) signal typically occurs in the IG. Only recently have projectors capable of receiving digital data become available. Most IGs are capable only of analog outputs to the projectors. The voltage range also varies for different IGs; some convert 0-255 digital to 0-0.75 v, while others convert to a 0-1 v or 0-2 v range.

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"gray" if they were lower. Because of the gamma nonlinearity, users also developed many rules of thumb governing their choice of relatively higher or lower codes for each "primary" color. The actual nonlinearity can be clearly seen in Figure 4, which shows (in both linear and logarithmic units) the red, green, and blue output of a Barco Calibrator CRT adjusted for maximum brightness and contrast.

Describing scene colors as RGB codes has proved to be so practical that artists and modelers often fail to realize how variable the results of these RGB descriptions can be. The RGB code functions like a recipe, giving information about the quantity of each ingredient (R, G, and B) to be included in the "mix" for a pixel area. But the resulting color can vary widely because there are many ways in which this "recipe" can be made inexact.

1. The "ingredients" may be quite different. Not all red phosphors are the same, and some will give reds which are decidedly more orange than others. None will give what most observers require for "true red," which is actually not a spectral color because true red requires a small amount of short wavelength ("blue") light. Green phosphors also differ in their intrinsic color, and most of them are too yellow to qualify as unique green (neither yellowish nor bluish). Blue phosphors may have a larger or smaller component of very short wavelength light; those with a larger component give a deeper (more violet) blue. The same RGB codes applied with different ingredients will clearly not be the same color.

2. The code representing "quantity" of a color does not actually represent an absolute quantity; it is a relative quantity. The digital code 255 is always intended to represent the maximum amount of a color which is available, but that maximum may differ from one case to another. All other codes are relative to that maximum; therefore, they will also vary when the maximum varies. Furthermore, the same code does not always give the same amount of color even on the very same device (such as a CRT). When the monitor's brightness or contrast controls are adjusted, the gamma functions and their maximum points will change.

Figure 5 presents the maximum red, green, and blue outputs of the six DART CRT projectors as a bar graph. The differences in bar heights illustrate the differences in luminous output which would be obtained by sending digital code 255 representing maximum voltage to each of the three electron guns serving each DART window.

3. The code representing quantity does not accurately control the proportions of R, G, and B in the mixture. Relative strengths of the three primaries at their maximum may differ from one CRT to another. Relative strengths ("balance") may also differ from one digital code level to another in the same device, so that the code

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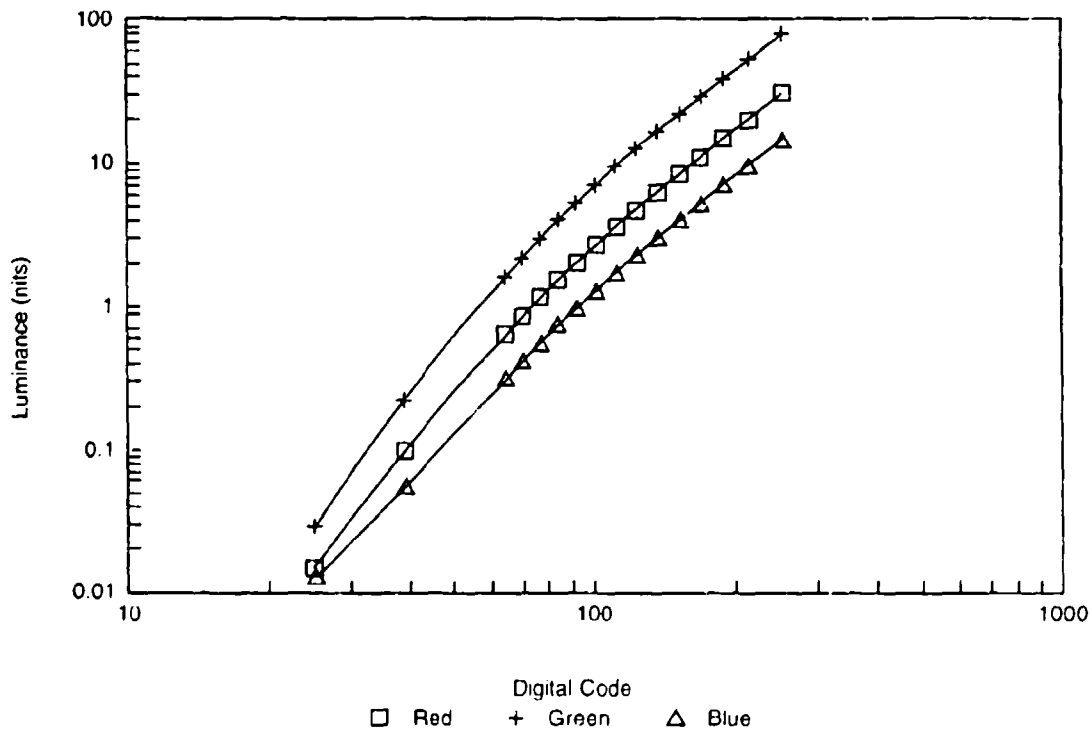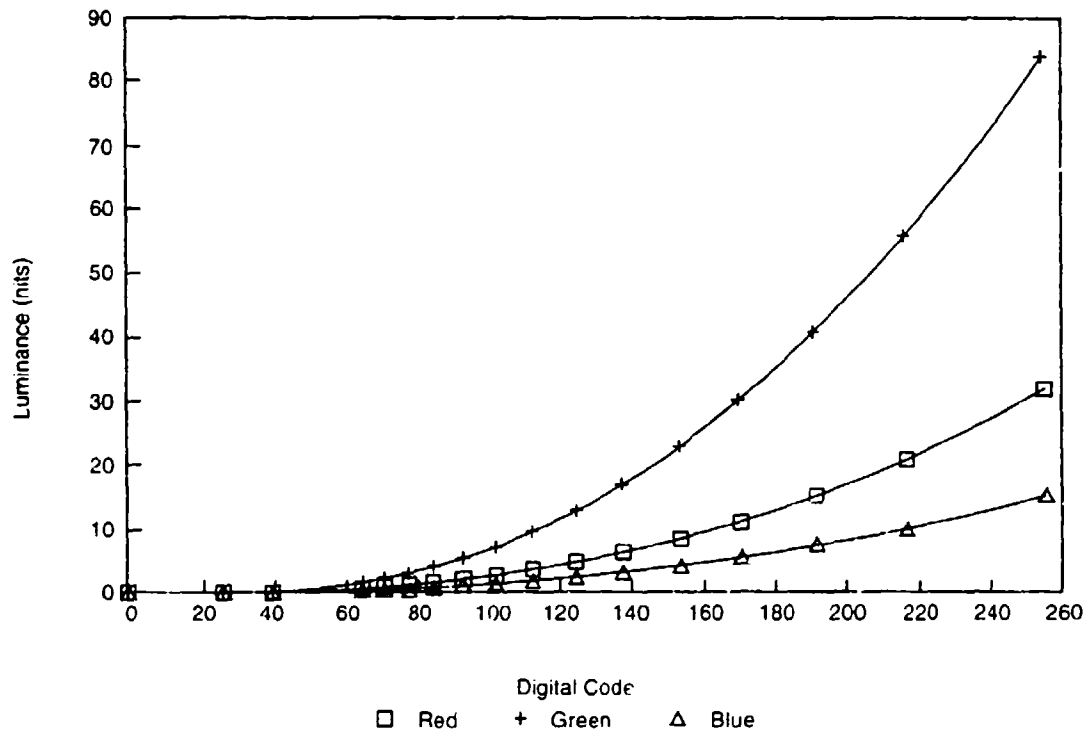
Barco Calibrator

Figure 4
Output Functions of a Barco Autocalibrator CRT [shown on
linear (top) and logarithmic (bottom) scales].   This
special monitor is designed for precision in color
performance.

Luminous Output of 6 DART Windows

Luminance (nits)

Red Green Blue

90 80 70 60 50 40 30 20 10 0

1 2 3 4 5 6
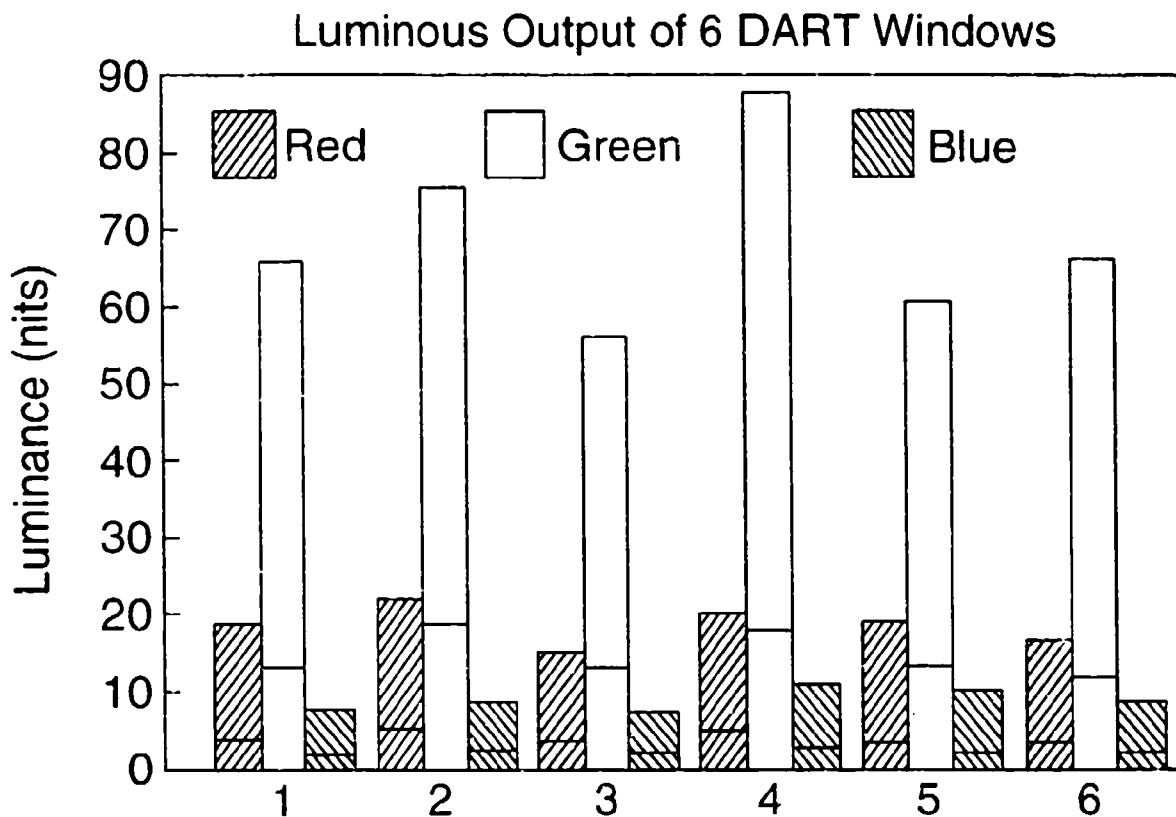
Figure 5
Luminous Output of Six DART Windows. Data obtained after
initial adjustment in July, 1990. Height of each bar
indicates maximum output (digital code 255); output at
digital code 128 is shown as a line within each bar.

"128, 128, 128" may not give a lower brightness of the same white
color as the code "255, 255, 255." Figure 5 also illustrates this
point; the 128-level for each primary is indicated by a mark in
each bar. Along with the brightness change may also come a color
shift, characteristic of the particular gamma functions for that
display. And again, changing the brightness and contrast settings
on a CRT will change the gamma functions as well as the maximum
output for each phosphor.

In short, specification of color as an RGB code--digital
specification of color--is quite unique to the display on which it
is developed and chosen. The same RGB code can give widely varying
results on other displays even of the same class. These facts will
be amply illustrated below.

The Practice of Display "Tweaking"

These problems with digital color control have not escaped the notice of digital display users. They are fully accustomed to finding each morning that yesterday's display colors are no longer quite "right." On the assumption that the RGB codes are inherently "right," the normal remedy is to readjust the display device so that the display colors look "better." Such readjustment is commonly called "tweaking."

Where a display has multiple sectors as in the DART display, tweaking is commonly used also as a method of getting at least similar color performance in all sectors. Such tweaking has to be done over again following the shift to a different database with a different set of RGB codes (that is, a different "color table").

Figure 6 shows the effect of tweaking the CRTs which serve the six DART windows. Each graph presents the luminance output of red, green, and blue phosphors in response to a set of digital codes which supply voltage to only one electron gun at a time. The top curve in each figure is the output of the green gun after all the six CRTs had been tweaked to provide the best match possible for a database with a single color table serving all six IG channels. Notice that all these curves depart from the shape illustrated in Figure 3. Instead of resembling a power function, these curves have an inflection point near their maximum output so that the curves bend toward an asymptote. Output functions having this shape indicate that the electron gun is being "overdriven," causing it to approach its maximum output at a relatively low digital code or voltage. As one would expect, the CRT in this group which had the highest maximum output (window 4) also shows the least amount of overdriving, while window 3 which had the lowest maximum output is overdriven already at a digital code of 160. Signs of overdriving are also seen in the corresponding curves for red and blue guns in each CRT.

The next highest curve in each figure is the output of the same gun after its CRT was adjusted to provide maximum brightness and contrast without appreciable overdriving. The procedure used in making such adjustments will be discussed below. An effort was made to get at least 60 cd/m^2 from each of the six green guns, but the final result shows the green output varying from 56 for window 3 to 88 for window 4.

Color Matching Through Individual Color Tables

Figure 6 indicates clearly that the colors produced by these six CRTs cannot possibly match when the six IG channels supplying the imagery share the same color table. Figure 7 illustrates the problem with respect to a single digital code (0,192,0), green alone at the digital level 192.

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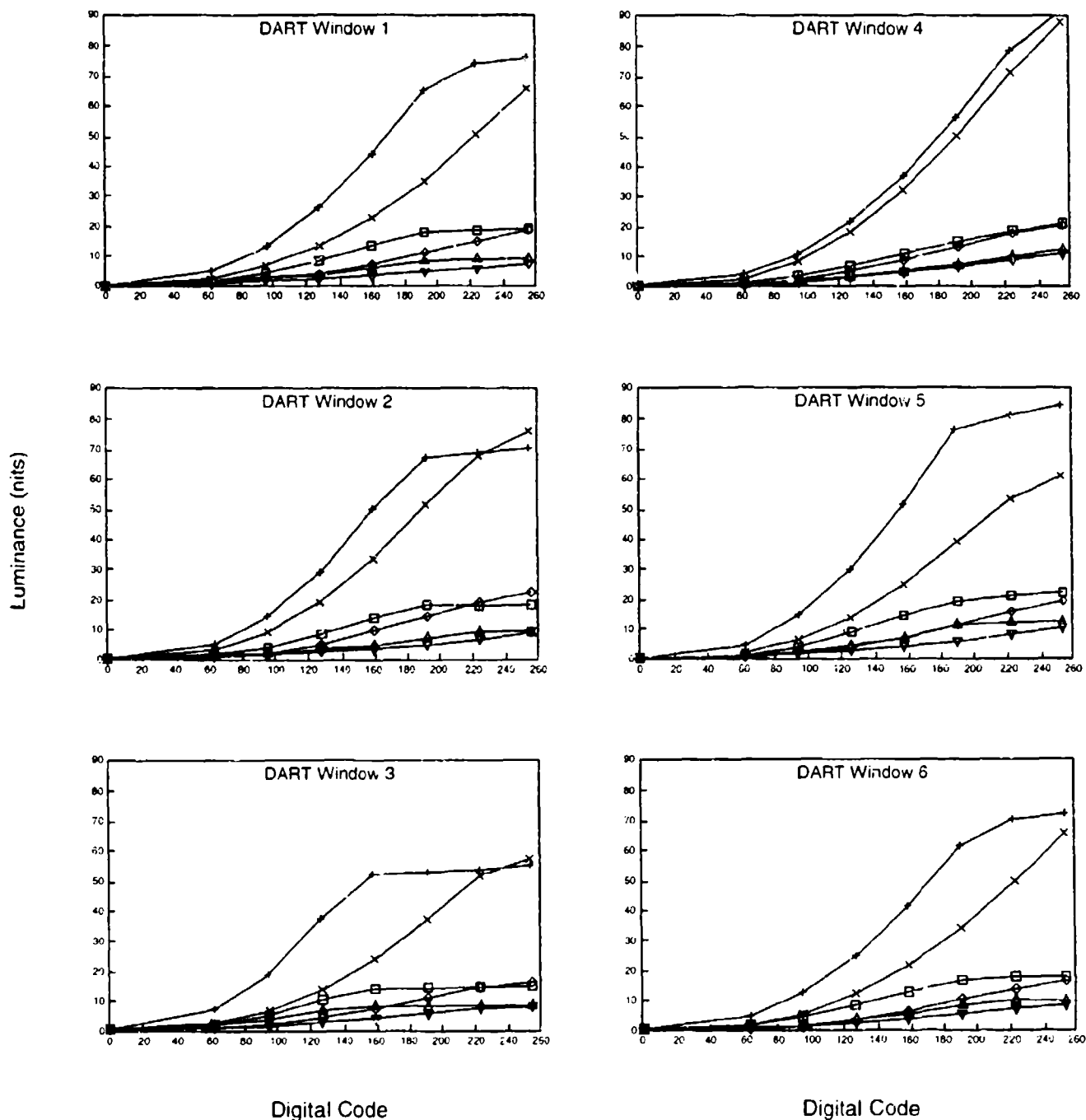
Figure 6
Output Functions of Six DART Windows. June 1990
following "tweaking" of controls to obtain approximately
equal performance from all windows; symbols are square
(red), plus (green), and upright triangle (blue). Note
the evidence of "overdriving" in all windows except
window 4. Output functions taken in July 1990, following
adjustment to avoid overdriving, are shown as diamonds
(red), cross (green), and inverted triangle (blue).
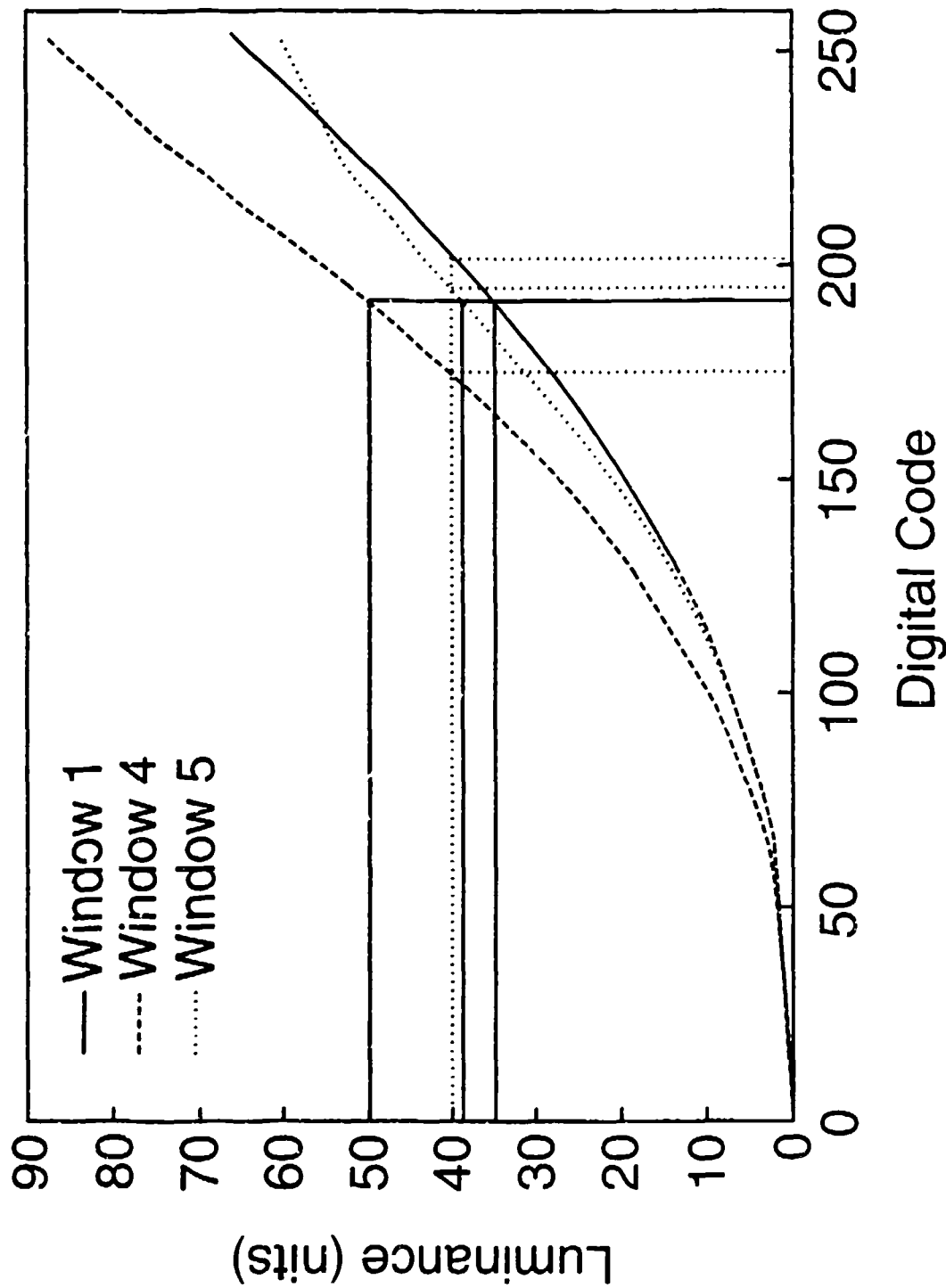
Figure 7

Output Matching Through Individualizing Digital Codes for Each Display. Green output of windows 1, 4, and 5 are shown as solid, dashed, and dotted curves, respectively. Solid straight lines show the varied outputs (on the luminance axis) which would be obtained from applying the same digital code (0,192,0) to all windows. Dotted straight lines show the different digital codes for green which would be needed to obtain the same output, 40 cd/m², from all windows.

In this figure, the green output curves are shown for the three DART windows most prominent in the pilot's forward field of view: window 1 in front, window 4 bordering it to the left, and window 5 bordering it to the right. As the solid lines reveal, window 1 will produce about 35 units of luminance; window 4, 50 units; and window 5, 38.7 units. However, it is possible to get all three windows to produce the same output, for example, 40 units of green. As the dotted lines reveal, this result will be obtained if we give *different* digital codes to each window: 0, 202, 0 to window 1; 0, 175, 0 to window 4; and 0, 195, 0 to window 5. The key to display color matching is found by providing an *individualized color table* for each device serving the display.

Developing six different color tables for a large database may seem to be a daunting task. Database color tables can contain up to 256 different entries, although few databases really use the maximum number. Fortunately, color science provides the methods needed for automatic calculation of the required digital codes from characterization data such as those shown in Figure 4.

For CRT-based display devices (such as the projection CRTs serving the DART), the following equation should be used to compute the tristimulus values of the display's output for a . RGB code:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M \begin{pmatrix} L_R \\ L_G \\ L_B \end{pmatrix} \tag{1}$$

where X, Y, and Z are the CIE tristimulus values of the color output, M is the chromaticity matrix for the display device, and L_R, L_G, and L_B represent the luminances of the red, green and blue outputs at the digital codes R, G, and B. The chromaticity matrix itself is formed from the x, y, and z chromaticity coordinates of the red, green and blue phosphors:

$$M = \begin{bmatrix} \dfrac{x_R}{y_R} & \dfrac{x_G}{y_G} & \dfrac{x_B}{y_B} \\ 1 & 1 & 1 \\ \dfrac{z_R}{y_R} & \dfrac{z_G}{y_G} & \dfrac{z_B}{y_B} \end{bmatrix} \tag{2}$$

To compute the red, green and blue luminances needed for obtaining a particular color described by tristimulus values, Equation 1 is inverted as:

$$\begin{pmatrix} L_R \\ L_G \\ L_B \end{pmatrix} = M^{-1} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad (3)$$

For most purposes, it is satisfactory to use Equation 1 to derive the XYZ values from characterization data for one device, then use Equation 2 to determine the RGB digital code for each of the other devices from its characterization data. Because most characterization files do not include actual measurements at every one of the 256 possible voltages, it is also necessary to interpolate between points actually measured. Post and Calhoun (1989) have shown that this interpolation is more successful when it is done in a piecewise linear manner than when it relies upon a functional relation (gamma or other function) between digital code and luminance output. They also recommend that the atrix used in Equation 1 and inverted in Equation 2 should be modified to reflect the voltage related variations in chromaticity of the red, green, and blue outputs. A more general treatment of XYZ, RGB, and other possible color spaces will be found in Howard (1992).

How Much Difference Will This Procedure Make?

Figures 8 and 9 indicate the size of luminance and chromaticity errors that can be expected before and after the procedure of computing individualized color tables (CTs) for display devices. All 181 ˈ ;B codes in the color table for a database representing the area around Fort Hunter Liggett were applied to each DART window, and the resulting colors were measured with the radiometer. The data are shown as differences from the output of window 1; luminance differences were computed as percent deviations from window 1 luminance, and chromaticity differences were computed as u'v' distances in CIE 1976 Uniform Chromaticity Space (UCS).[3] Open circles in Figure 8 represent the frequency of luminance errors in ranges of 10 percentage points centered at scale positions from -40 to +40%. Open circles in Figure 9 represent the frequency of chromaticity errors in ranges of .0025 centered at scale positions from .001 to .021, with a final scale position incorporating all the remaining larger errors.

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[3]Chromaticity coordinates u' and v' are derived from XYZ tristimulus values: $u' = 4X/(X + 15Y + 3Z)$, and $v' = 9Y/(X + 15Y + 3Z)$.
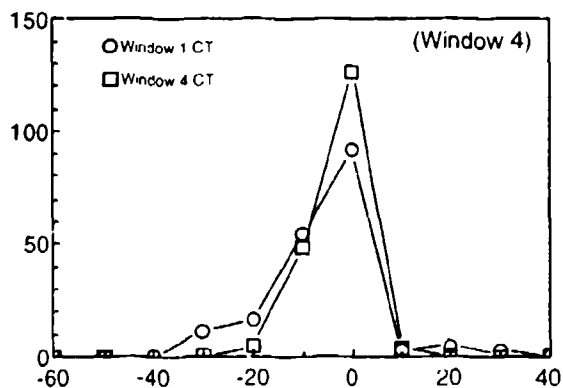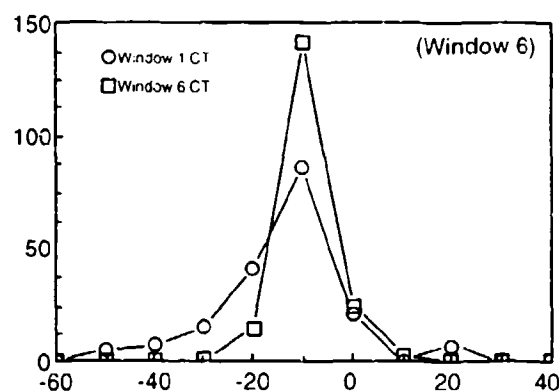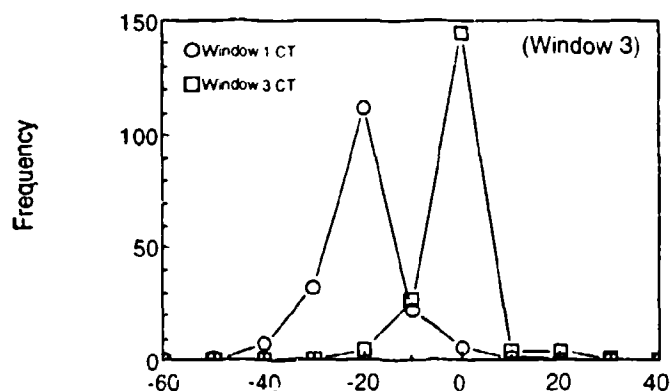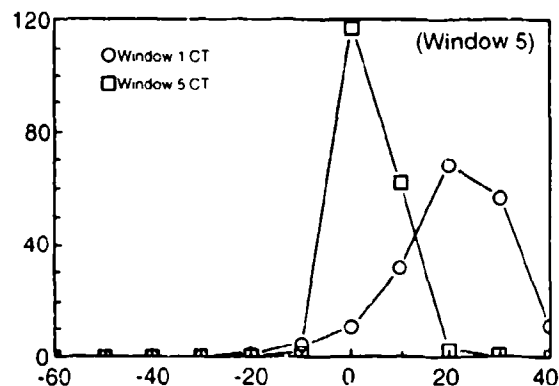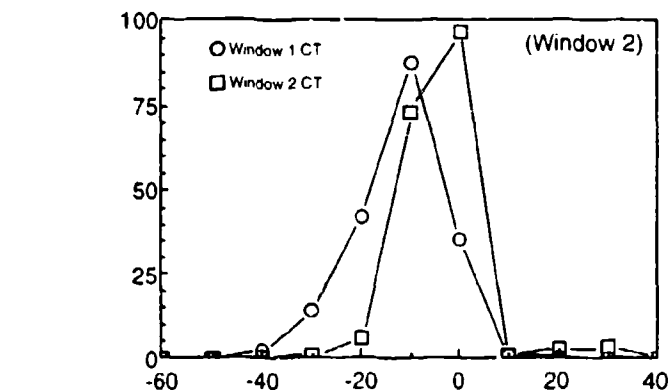
Per Cent Difference from Window 1

Figure 8

Luminance Errors. Graphs showing the differences in luminance performance between window 1, the reference window, and each of the other windows for a representative set of 181 database colors. Percent difference in luminance is shown on the abscissa. Open circles show the frequency of occurrence of differences in each size range when all windows were given the same digital color table as window 1. Open squares show the frequencies of these differences when each window was given an individualized color table based on its own characterization file.

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Distance in u'v' Space
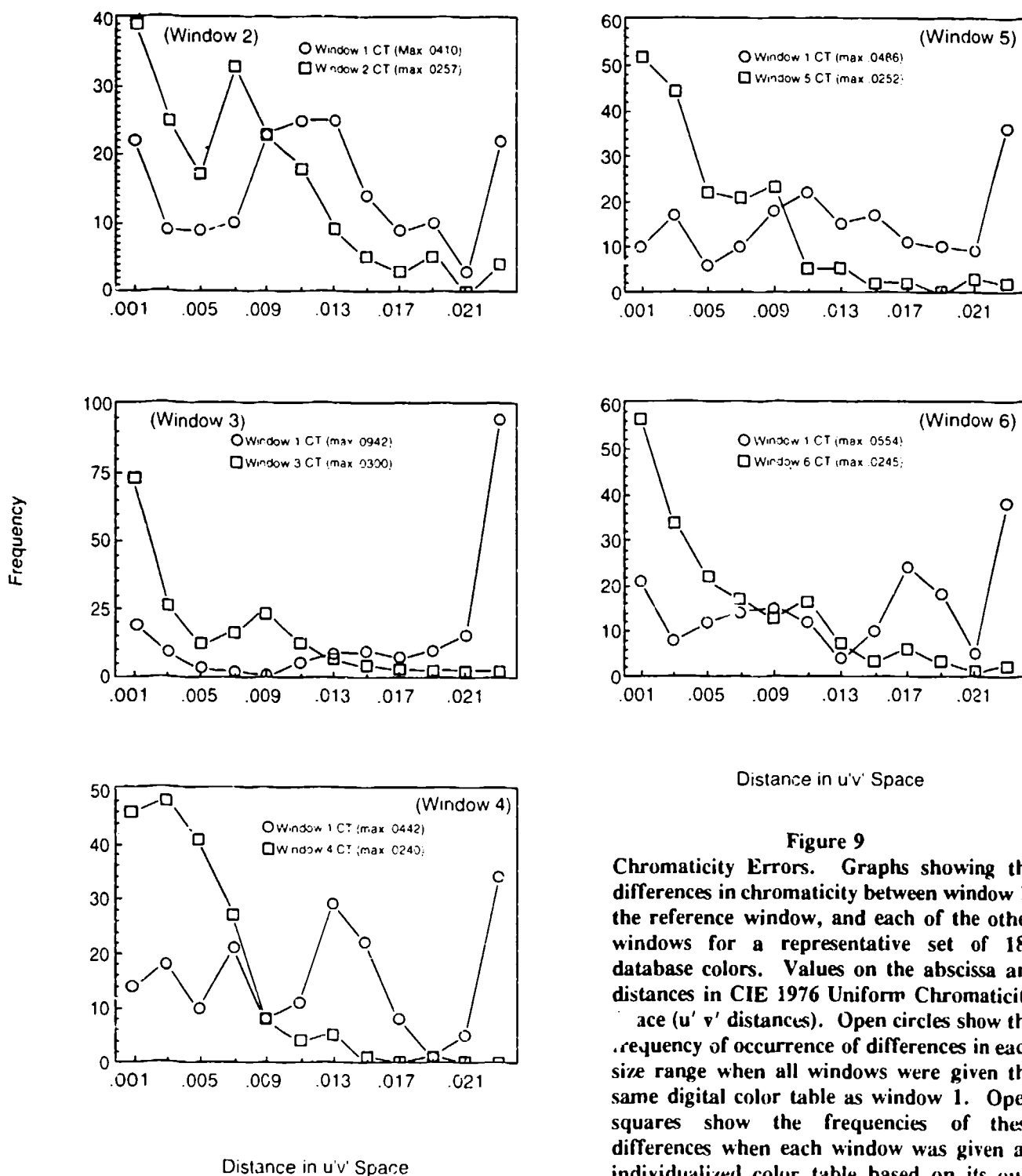
Figure 9

Chromaticity Errors. Graphs showing the differences in chromaticity between window 1, the reference window, and each of the other windows for a representative set of 181 database colors. Values on the abscissa are distances in CIE 1976 Uniform Chromaticity ace (u' v' distances). Open circles show the frequency of occurrence of differences in each size range when all windows were given the same digital color table as window 1. Open squares show the frequencies of these differences when each window was given an individualized color table based on its own characterization file.

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Then, taking the performance of window 1 as the standard, new color tables were computed for windows 2-5 by the procedure outlined above, and the resulting colors were measured. These colors were compared with window 1 output in the same way, and the frequency of differences is shown by open squares in Figures 8 and 9. Luminance errors greater than 10% and chromaticity errors greater than .01 occur much less frequently when special color tables have been computed for each window. Maximum chromaticity errors appear alongside labels within each graph.

Howard (1993) provides additional data on chromaticity errors observed when all DART windows receive the same digital codes as window 1.

Automating the Color Control Process

During the past five years, Armstrong Laboratory has developed computer programs which automate the process of acquiring characterization files from each display device and the computation of device-specific color tables from these files. Automated characterization is performed by the Computerized Colorimetry System (CCS), a C program running on a Compaq personal computer with a special card provided to interface with the Photo Research PR703-PC spectroradiometer. The measurement program (CCS-Measure) uses a list of RGB codes, called a Color Code File (CCF), that includes 16 levels of each primary alone and 2 additional codes for zero (0,0,0) and maximum output (255,255,255). The PC sends these codes, one at a time, to the display controller, receives a confirmation that the coded color is being displayed, signals the radiometer to make a measurement, and receives a measurement file from the radiometer. The program compiles these measurements into a characterization (CZN) file containing the required data about the display device. The CCS program has been described in greater detail by Howard (1990).

CZN files from the six DART windows are transmitted to another C program, the Color Modeling Workstation (CMW) running on a Silicon Graphics Personal IRIS. The CMW converts each CZN file into a detailed description of the color gamut of that device in CIE 1976 L*u*v* (CIELUV) space. This space is an approximately uniform three-dimensional color space. In order to make the transformation from XYZ space into CIELUV, it is necessary to specify the luminance and chromaticity coordinates of a reference white. The CMW is given a reference white luminance of 70 cd/m^2, below the maximum white output of the brightest window but above the maximum white of the dimmest window. D65 daylight is taken as the reference chromaticity; its x,y-chromaticity coordinates are .31, .33. The CMW can then display the color gamuts of any two DART windows simultaneously in its graphic display, and the user can determine whether individual database colors fall within the gamuts achievable by each device. For each color selected, the

display computes and displays individual RGB codes for each device. The program includes utilities which enable the user to store these RGB codes in individually tailored database color tables for use by the IG. The CMW is described more fully by Garrett, Hepner, and Howard (1993).

The results of these computations have provided satisfactory color matches for most scene elements. However, the computed codes frequently result in only approximate matches for large background colors such as sky, ground, and forest. To eliminate the remaining color discrepancies for such areas, the CCS program's "measure and adjust" procedure is used. With the radiometer again directed to one DART window at a time, CCS uses a Color Request File (CRF) containing the tristimulus values of these major background colors as displayed by the reference window (usually window 1). The PC then computes a best-guess at the RGB code required to produce that color on the display device being measured. It directs the display controller to send that RGB code to the display device and sends a measurement command to the radiometer. The result is reported back to the PC, which compares the XYZ obtained with the XYZ requested, applying tolerance limits set by the user.[4] If the obtained XYZ is within tolerance, the RGB code is stored and the PC then proceeds to the next XYZ on the list. If the measured XYZ is not close enough to the requested values, the PC then computes the RGB which would (given the device characterization file) be mathematically expected to produce the obtained XYZ, compares this RGB with the first one, and computes the direction and amount of change in the first code which should be required to improve the match. This iterative loop continues for a limited number of cycles. Usually a satisfactory RGB code is found within 1 to 3 cycles.

Selection of RGB codes through the CCS measure-and-adjust program produces a file of adjusted (ADJ) color codes which are transmitted to the CMW for inclusion in the device color table. Codes tagged as coming from an ADJ file are not subject to modification by the CMW.

Color Problems Produced by Texturing

Texture patterns applied to polygon faces in the database enhance detail in the computer-generated imagery without consuming feature resources. The technique known as "texturing" modulates face colors on a subpixel basis without the use of edges.

The image generator in use at Armstrong Laboratory (called the Advanced Visual Technology System, or AVTS) is a predecessor of the General Electric CompuScene IV. In AVTS, a "texture map," usually

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[4]Armstrong Lab sets tolerance limits at a u'v' distance of .01 for chromaticity and 5% for luminance in simulator displays. For vision research, chromaticity tolerance is set at .0015.

derived from a monochrome photograph, indicates the gray level to be applied at each point on the face, and these gray levels are converted to coefficients which will act as multipliers on the red, green, and blue digital codes assigned to that face. The coefficient is 1 for the average gray level in the texture map. Lighter points will have coefficients greater than 1; darker points will have coefficients less than 1.

Such a texturing system is designed to produce lightness variations without changing the face color. Proportional changes in red, green, and blue output would be expected to result in varying lightnesses of the same face color. But proportional changes in red, green, and blue *digital codes* do not entail proportional changes in output unless the output functions of the red, green, and blue guns are very similar. Figure 10 shows that this is not the case for the projection CRTs operating in the DART.

The output functions in Figure 10 are shown in logarithmic coordinates. If output was really a power function of voltage, these functions would all be straight lines in a log-log plot. The green output actually is almost linear for all the windows. The blue output is somewhat linear above the voltage represented by a digital code of 64. The red output, however, is quite nonlinear; red output is higher than blue at maximum voltage, but it drops more rapidly, crossing over the blue output and approaching zero at digital code 64. This relative loss of red and blue at low digital codes implies that the darker shades of any face color will be green, regardless of the original assigned color. With this type of IG and these display devices, it is not possible to have a textured face which remains yellowish or tan or gray at its lowest lightness levels. This problem has generally been avoided in the DART by designing texture colors (other than green) so that no red or blue digital codes below 92 will be called. In order to meet this requirement, contrast within the texture pattern usually has to be significantly diminished, and special attention has to be given to the textures case by case.

Such texture color problems could be remedied by improving the IG, enabling it to compute texture lightness levels by operating on the Y tristimulus value of the intended color before converting the color's XYZ values to RGB codes. This change is simple in principle, but few of the currently available IGs are designed to implement it. Given a color table of XYZ tristimulus values, all computations in the IG could be performed on these values; conversion to RGB could be accomplished by way of a lookup table, specific to each display device, at the final stage before voltage signals are sent out.

The texture color problems encountered in the DART could also be addressed by increasing the red and blue output of the display devices. This possibility will be discussed in the section dealing
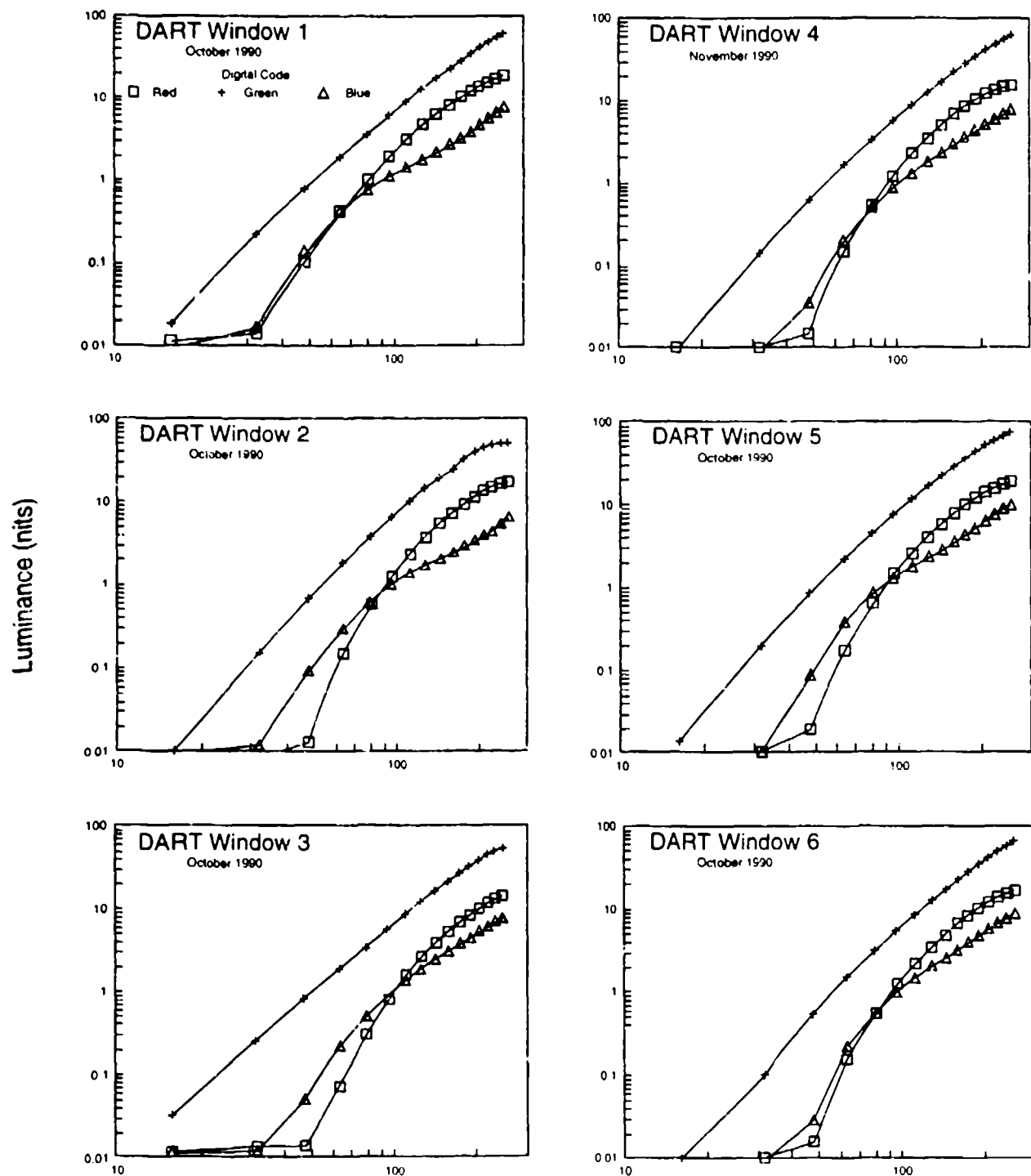
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Figure 10
Log/Log Plots, October/November 1990. Characterization
data on the six DART windows, measured in October/
November 1990. The data are shown as double logarithmic
plots to illustrate the loss of linearity by red and blue
components at lower voltage levels. Data for red
components are plotted as squares, for green as plusses,
and for blue as triangles.

with performance of the DART CRTs over the 32-month period from July 1990 to March 1993.

Performance of DART CRTs Over Time

This section will address two questions: What procedure should be followed in setting up the display devices for characterization? How often should the characterization process be repeated?

Characterization files for the DART CRTs have been obtained at approximately 6-month intervals over a 32-month period. Results of the first two sets of measurements have already been presented in Figure 6 in order to show that projectors are likely to be overdriven when "tweaking" is used to match colors across displays. After obtaining the "tweaked" measurements in June 1990, all projectors were carefully adjusted according to the manufacturer's instructions and remeasured in July. Positions of the brightness and contrast knobs on the remote control boxes were marked with ink, and these positions were maintained without change until after the measurements that were made in January 1993.

This adjustment procedure was carried out individually for each window. First, the built-in gray scale was displayed by the projector, and the red and blue guns were turned off. While observing the eight vertical bars containing graded amounts of green light, the brightness and contrast knobs on the remote control box were adjusted to give maximum brightness and contrast. That is, the darkest green was adjusted to appear almost black, yet distinctly darker than the neighboring bar, while maintaining as high a brightness setting as possible. The drive setting for the green component was set as high as possible without overdriving. Once the green adjustments had been made, the red and blue components were turned on again, and their drive settings were adjusted to give as good a gray scale as possible. However, it was not possible to achieve a setting which appeared neutral at both the white and dark ends of the scale. The gray scale appeared white at the top levels but greenish at the lower levels. The reasons for this appearance have already been discussed above.

Table 1 provides the maximum red, green, and blue outputs for each window at the beginning and end of the period July 1990 to January 1993. Figure 11 graphs the change in maximum output during this period for each primary and each window. During this period, all windows except window 5 were served continuously by the same projector. The projector serving window 5 was changed in August 1990; this change explains the increase in green output between months 0 and 3 for window 5.

CRT phosphors are subject to decay over time, and these graphs show the expected decline in maximum luminance for the red, green,

Table 1.   Luminance Changes over 30 Months (all luminances in cd/m^2)

Window	Red CRT		Green CRT		Blue CRT	
	7/90	1/93	7/90	1/93	7/90	1/93
1	18.8	15.5	65.9	54.6	7.64	2.66
2	22.1	18.2	75.3	61.4	8.69	2.94
3	15.2	12.9	56.1	44.4	7.22	3.39
4	20.2	13.2	87.7	49.8	10.8	5.19
5	19.0	17.5	60.6	64.0	10.1	5.71
6	16.7	14.9	66.3	54.9	8.65	4.53

and blue phosphors in most windows. The average luminance loss is 18.5% for green, 17% for red, and 55% for blue. These data indicate that characterization data need not be obtained more frequently than every six months. The relatively large change in blue output provides good evidence of the need for revising device color tables each time new characterization data are obtained.

During the six weeks following the January 1993 measurements, channel-switching arrangements for the DART were completely overhauled to accommodate the addition of the ninth DART window. Signals from the IG to the projectors have always incorporated two stages, a first stage from the IG to the channel-switching box and a second stage from the channel-switching box to the projectors. Prior to 1993, the switching box was located relatively near the IG and relatively far from the DART. The new arrangement relocated the switching box close to the DART and included voltage boosters in that box. No one was able to predict how these changes might affect performance of the projectors.

However, once these changes were in place, it became immediately apparent that the color matching between windows had been lost. Radiometric measurements showed that the January characterization files no longer described the CRTs' outputs. Some of these measurements also suggested that there had been a paradoxical *increase* in the luminous output of certain projectors. We concluded that the change in wiring had increased the efficiency of the projectors, and we decided to readjust the brightness, contrast, and drive settings.
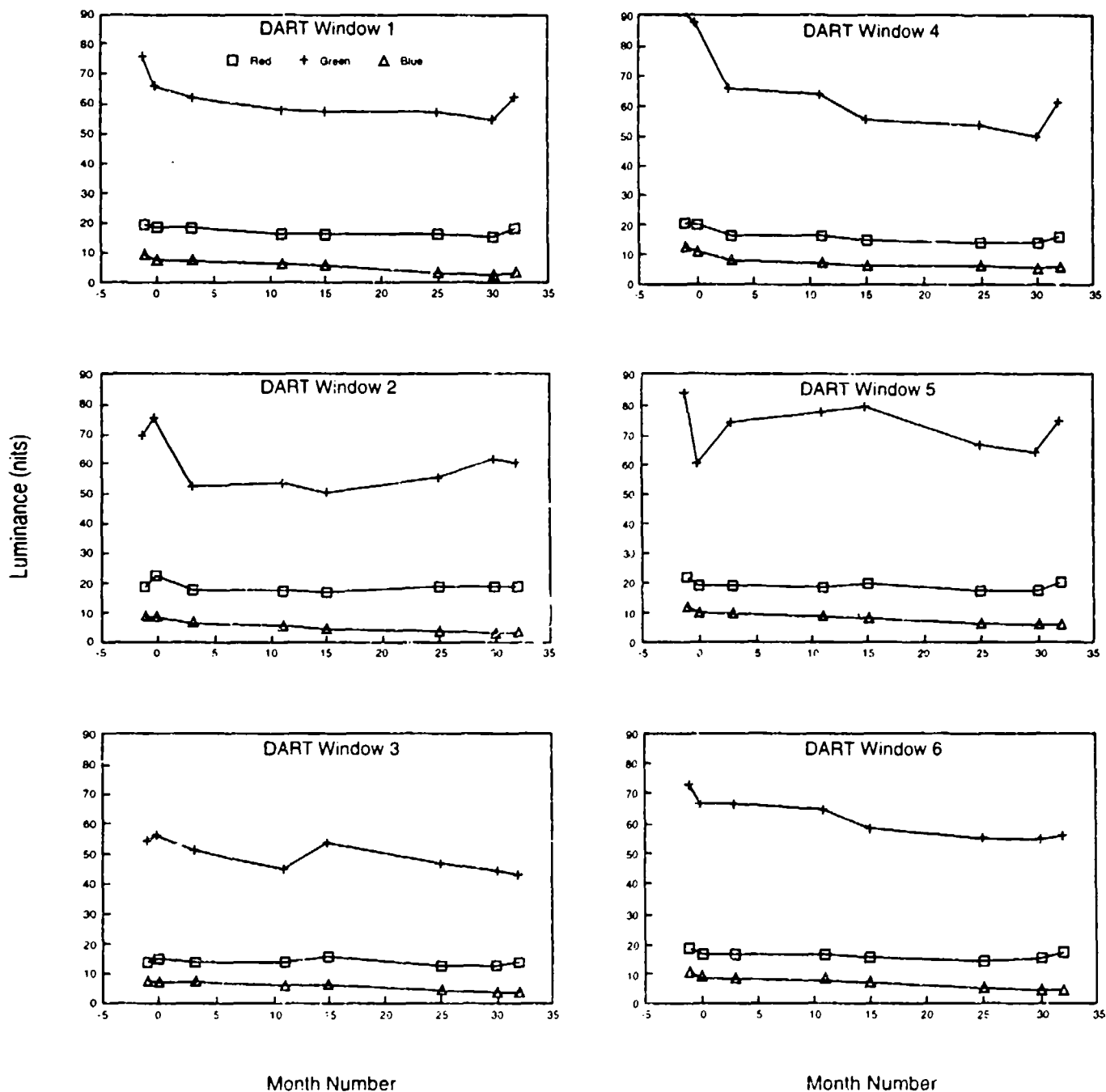
Figure 11

Luminance Change Over Time. Maximum luminous output of red, green, and blue CRTs in each DART window, measured over a 33-month period. Baseline month is taken as July 1990 and indicated by 0; measurements taken the previous month, when the CRTs had been adjusted by tweaking, are plotted at month -1. Month 30 is January 1993; month 32 is March 1993. Data for red components are plotted as squares, for green as plusses, and for blue as triangles.

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In this readjustment, we first measured the output function of the green component. When it showed overdriving, we revised the brightness and/or contrast settings to give a function that was more linear in log/log coordinates. We then *increased* the drive settings for the red and blue components, making their log/log functions as linear as possible. By this method, we found we were able to improve the performance of the red and blue components at low voltage levels. Figure 12 shows the log/log output functions obtained in March 1993 after the switching changes and subsequent readjustments. Compared to the January data (Fig. 10), all windows except windows 2 and 3 showed increases in maximum green output. All windows showed some gain in maximum red output, and all log/log plots increased in linearity. Numerical data from the March 1993 characterization of window 1 are provided in Table 2.

Nevertheless, as the projectors in windows 1-6 approached the end of their third year of service, we encountered unexpected difficulties in obtaining satisfactory color matches. The reason for the difficulties became visually apparent when the IG displayed a field of uniform color in all windows; under these conditions, a "horizon line" could be seen dividing a slightly bluer lower region from a less-blue upper region. Clearly, the decline in blue phosphor response had been greater for those parts of the windows which normally displayed blue sky during straight-and-level flight. Since our characterization measurements were made on a square at the center of each window, the measurements for windows 4 and 5 came from a region *below* the horizon line, while measurements for the other windows came from a region above that line. We were able to restore satisfactory color matching by shifting the measurement square in windows 4 and 5 to a higher position.

In light of these data on declining performance, display engineers decided that the component CRTs in all DART projectors should be replaced. These CRTs have seen varying amounts of service over the past three to four years; windows 1-6 were in operation longer than windows 7 and 8. Records indicate about 4,400 total hours of operation for window 1 by the end of March 1993.

CONCLUSION

This report recommends the following principles for obtaining optimal color performance in displays served by several display devices:

1. Database colors should be defined in device-independent terms, using the CIE system of XYZ tristimulus values. Digital RGB codes for driving the display devices should be derived from these XYZ values by the standard colorimetric equations.
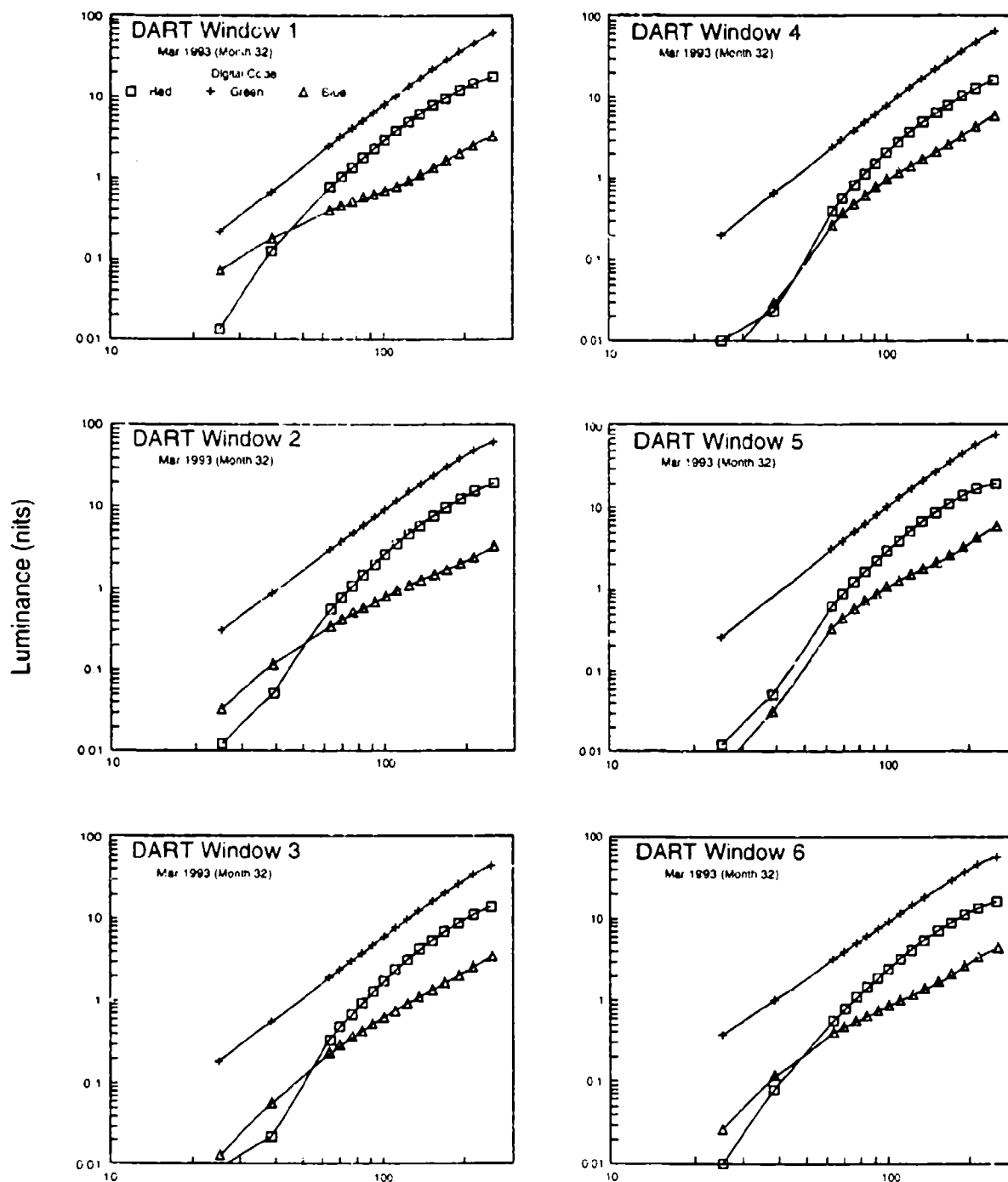
Figure 12

Log/Log Plots, March 1993. Characterization data on the six DART windows, measured in March 1993. The data are shown as double logarithmic plots for comparison with Figure 10. Data for red components are plotted as squares, for green as plusses, and for blue as triangles.

Table 2. Sample Characterization File: Window 1, March 1993 (luminance in cd/m²)

R	G	B	X	Y	Z	x	y	u'	v'
0	0	0	0.009	0.008	0.006	0.3973	0.3329	0.2563	0.4832
25	0	0	0.021	0.013	0.006	0.5276	0.3256	0.3606	0.5008
39	0	0	0.237	0.124	0.005	0.6475	0.3383	0.4492	0.5282
64	0	0	1.513	0.784	0.013	0.6550	0.3394	0.4547	0.5301
70	0	0	1.992	1.034	0.018	0.6546	0.3396	0.4541	0.5301
77	0	0	2.647	1.372	0.022	0.6550	0.3395	0.4546	0.5301
84	0	0	3.400	1.763	0.027	0.6551	0.3396	0.4546	0.5302
92	0	0	4.379	2.27	0.035	0.6550	0.3397	0.4544	0.5302
101	0	0	5.624	2.913	0.046	0.6552	0.3394	0.4548	0.5302
112	0	0	7.340	3.804	0.056	0.6553	0.3396	0.4547	0.5302
124	0	0	9.437	4.888	0.081	0.6551	0.3393	0.4548	0.5300
137	0	0	12.018	6.229	0.102	0.6550	0.3395	0.4546	0.5301
153	0	0	15.291	7.927	0.128	0.6550	0.3395	0.4545	0.5301
170	0	0	19.040	9.877	0.165	0.6547	0.3396	0.4542	0.5301
191	0	0	23.737	12.306	0.214	0.6547	0.3394	0.4544	0.5300
216	0	0	29.113	15.103	0.266	0.6545	0.3395	0.4541	0.5300
255	0	0	35.236	18.302	0.343	0.6540	0.3397	0.4535	0.5300
0	0	0	0.009	0.008	0.006	0.3973	0.3329	0.2563	0.4832
0	25	0	0.129	0.215	0.037	0.3388	0.5644	0.1490	0.5585
0	39	0	0.388	0.672	0.094	0.3364	0.5820	0.1445	0.5625
0	64	0	1.457	2.499	0.355	0.3380	0.5797	0.1457	0.5622
0	70	0	1.847	3.167	0.446	0.3383	0.5800	0.1458	0.5623
0	77	0	2.375	4.068	0.575	0.3384	0.5797	0.1459	0.5622
0	84	0	2.958	5.064	0.714	0.3386	0.5796	0.1460	0.5622
0	92	0	3.735	6.399	0.900	0.3385	0.5799	0.1459	0.5623
0	101	0	4.743	8.122	1.148	0.3384	0.5796	0.1459	0.5622
0	112	0	6.121	10.481	1.479	0.3385	0.5796	0.1459	0.5622
0	124	0	7.881	13.482	1.897	0.3388	0.5796	0.1461	0.5623
0	137	0	10.072	17.213	2.447	0.3388	0.5789	0.1462	0.5621
0	153	0	13.118	22.440	3.181	0.3386	0.5793	0.1461	0.5622
0	170	0	16.707	28.575	4.029	0.3388	0.5795	0.1461	0.5622
0	191	0	21.741	37.201	5.258	0.3386	0.5795	0.1460	0.5622
0	216	0	27.906	47.686	6.772	0.3388	0.5790	0.1462	0.5621

Table 2 (concluded)

R	G	B	X	Y	Z	x	y	u'	v'
0	255	0	36.454	62.315	8.849	0.3387	0.5790	0.1461	0.5621
0	0	0	0.009	0.008	0.006	0.3973	0.3329	0.2563	0.4832
0	0	25	0.069	0.072	0.328	0.1464	0.1531	0.1288	0.3032
0	0	39	0.174	0.174	0.908	0.1382	0.1386	0.1260	0.2844
0	0	64	0.434	0.403	2.339	0.1366	0.1268	0.1286	0.2687
0	0	70	0.498	0.458	2.684	0.1369	0.1259	0.1292	0.2674
0	0	77	0.564	0.512	3.046	0.1368	0.1243	0.1297	0.2652
0	0	84	0.631	0.568	3.396	0.1373	0.1237	0.1304	0.2644
0	0	92	0.694	0.621	3.776	0.1362	0.1220	0.1300	0.2620
0	0	101	0.777	0.695	4.205	0.1369	0.1224	0.1306	0.2626
0	0	112	0.889	0.791	4.825	0.1367	0.1216	0.1306	0.2614
0	0	124	1.042	0.929	5.647	0.1368	0.1219	0.1306	0.2619
0	0	137	1.209	1.089	6.545	0.1367	0.1232	0.1300	0.2636
0	0	153	1.431	1.312	7.727	0.1367	0.1253	0.1292	0.2666
0	0	170	1.691	1.593	9.103	0.1365	0.1286	0.1279	0.2710
0	0	191	2.032	1.995	10.863	0.1365	0.1340	0.1260	0.2781
0	0	216	2.442	2.512	12.943	0.1364	0.1403	0.1237	0.2863
0	0	255	2.957	3.252	15.416	0.1367	0.1504	0.1207	0.2987
0	0	0	0.009	0.008	0.006	0.3973	0.3329	0.2563	0.4832
25	25	25	0.200	0.281	0.352	0.2404	0.3370	0.1465	0.4621
39	39	39	0.799	0.970	1.000	0.2887	0.3502	0.1743	0.4758
64	64	64	3.355	3.645	2.722	0.3451	0.3749	0.2028	0.4956
70	70	70	4.226	4.569	2.976	0.3590	0.3881	0.2069	0.5034
77	77	77	5.547	5.912	3.709	0.3657	0.3898	0.2106	0.5050
84	84	84	6.873	7.402	3.657	0.3833	0.4128	0.2133	0.5169
101	101	101	11.020	11.687	5.181	0.3951	0.4191	0.2184	0.5210
112	112	112	14.276	14.972	6.507	0.3993	0.4187	0.2210	0.5215
124	124	124	18.227	19.211	7.419	0.4063	0.4283	0.2218	0.5261
137	137	137	22.928	24.188	9.246	0.4068	0.4292	0.2218	0.5265
153	153	153	28.810	30.551	10.884	0.4101	0.4349	0.2217	0.5290
170	170	170	34.863	37.049	13.263	0.4093	0.4350	0.2212	0.5289
191	191	191	43.032	46.206	15.756	0.4099	0.4401	0.2197	0.5308
216	216	216	54.619	59.412	20.337	0.4065	0.4422	0.2170	0.5311
255	255	255	73.2?9	81.774	27.191	0.4022	0.4487	0.2122	0.5327

2.   Color-matching between component displays can best be achieved through computation of individualized color tables, based on characterization data from the individual displays.

3.   Initial adjustment of the display devices should be done with great care to obtain the highest brightness compatible with good contrast. The output functions should be brought as close to log-log linearity as possible.

4.   These initial adjustments should be carefully preserved and guarded against accidental or intentional changes once the characterization measurements have begun.

5.   As long as the display system (including IG, connecting hardware, and display devices) remains the same, the output functions will retain their general shape in spite of a gradual decline in luminance. Characterization should be repeated about every six months.

6.   If new characterization files for a particular device indicate any disproportionate change in its green component, this component may be optimized by slight adjustment of the device's brightness or contrast settings. Changes in the red or blue components should be compensated by adjusting the drive setting.

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